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Evaluation of Damage to Carbon-Fibre Composites Induced by Self-Pierce Riveting

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Abstract

The damages to fibre-reinforced plastics induced by the self-pierce riveting process are to be analysed and evaluated in a research project. A method was developed for the preparation of test specimens depicting the solid self-pierce riveting process, which allows the evaluation in X-ray computed tomography of defects such as delamination. Correlations of process influences and material variants are determined with the damage so that they can be minimized. In quasi-static and cyclic tests the extent of damage on laminate strength and load carrying capacity of joints will be investigated.

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Keywords: Delaminations, Self-Pierce Riveting, Composite, Computer Tomography, Punching

1. Introduction

Ecological, economic and legislative forces are compelling the automotive industry to minimize fuel consumption. A high potential for success is attributed to lightweight design, as all resistors of a vehicle in motion except air resistance correlate directly with its mass. Therefore, more and more composite materials are finding their way into vehicles, as these enable a high degree of lightweight designdue to their excellent specific mechanical properties. Hybrid structures with composites and conventional metallic materials create synergies, resulting from the optimal use of specific properties in the right place.

The realization of such lightweight structures requires a material-oriented and efficient joining technology, which is essential for ensuring the functionality of a vehicle. Mechanical joining methods without preholes, such as solid self-pierce riveting, are able to create viable composites in a very short time. Especially if an additional adhesive is used, components can be fixed efficiently to each other and need not be held or clamped until the adhesive is cured.

However, it should be noted that the holes cannot be pierced without damaging the fibre-reinforced plastic. Due to their heterogeneous material structure a clear different shear-cutting behaviour is observed. Since composite materials usually exhibit no ductility and thus stress peaks cannot be degraded plastically, material damage in the form of cracks and fractures is induced in the edge region during the hole-punching process. These defects can be fibre fracture, classic inter-fibre failure and interlaminar cracks i.e. delaminations. Figure 1 shows delaminations around a punched hole.

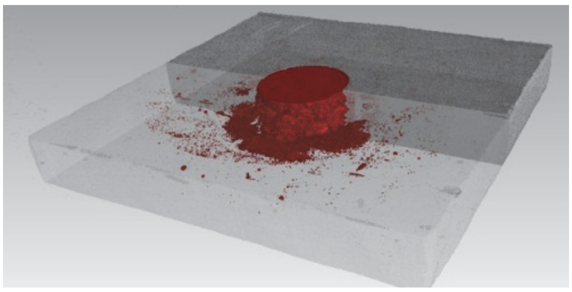

Fig. 1. Volumetric computed tomography scan of delaminations around a punched hole in carbon fibre reinforced plastic

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The latter, in particular, are to be regarded as critical because delaminations endanger the component stability due to reduced bending stiffness, and can lead to premature catastrophic failure of structures. Delaminations are planiform cracks between two layers in a laminate and therefore represent a special form of inter-fibre breaks. As a rule no fibre reinforcement exists between the layers in classical fibre composites, so delaminations are able to grow without major hindrance particularly under sufficiently large cyclic loading [1]. Since layers are separated, they can easily buckle under compressive stress, which is why failure can occur at an early stage.

Delaminations are induced in the fibre-reinforced plastic primarily during the punching process. When punching through the composite, the crack grows from the surface and is stopped at differently oriented layers. Whereas individual layers are cut and spring back elastically, the remaining layers are pushed further down as shown in Fig. 2. Thus in the interlaminar planes at the end of the slug, harmful peeling stresses are formed that take the main responsibility for the emergence of delaminations [2]. Furthermore, when driving in the rivet, friction occurs between the rivet shank and the hole wall, thereby creating transverse forces in the direction of movement and opening existing delaminations even further.

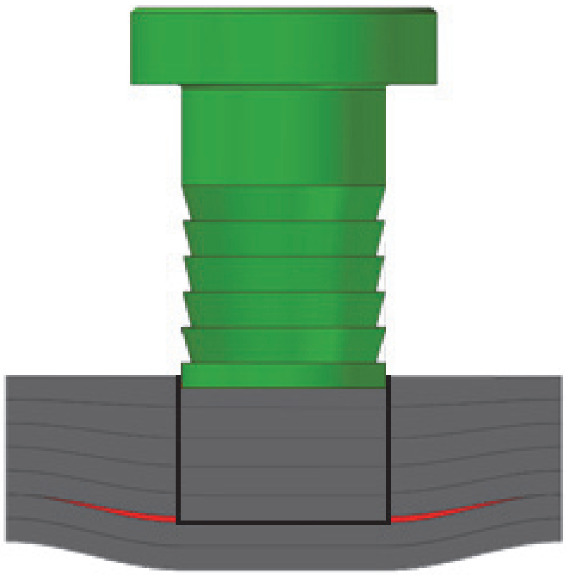

Fig. 2. Push-out delaminations caused by the punching process

At present, no knowledge exists about how strong the defects that are induced in the composite material by the punching process are, or what potential harm emanates from them. It is be conceivable that delaminations can be tolerated to a certain degree, especially if they are located in the region under the flat head of the rivet.

Therefore a research project is to investigate how seriously the fibre-reinforced plastic is damaged during self-pierce riveting and what consequences this has for the joint. For this purpose, samples are prepared under conditions similar to the actual process and checked for damage using non-destructive testing methods. Introduced defects should be minimized by sensible adjustments to the process parameters. Furthermore, strength tests on punched fibre composite material samples are planned, as well as a determination of parameters of simple overlapped shear tension samples with different degrees of damages.

2. Experimental Procedure

In order to detect damage in fibre composite components, non-destructive test methods must be used so that the component remains intact. Since CFRP is black and opaque, inner defects cannot be detected visually by the human eye. Other methods must be used instead, such as ultrasound, pulse thermography or Lamb wave interferometry [3]. At present, however, X-ray computed tomography offers the best resolution for detecting damage in composite materials, which is why this method is particularly suited for detecting delaminations in self-pierce riveted samples [4]. The good detection capability offers the possibility of describing damages not only in form and position, but also quantitatively.

For the proper detection of delaminations using computer tomography, it is advisable to prepare self-pierce riveted FRP-metal samples in such a way that the composite material can be irradiated isolated from metal components. As metals such as steel and polymeric materials usually differ greatly in their density and their ability to absorb X-rays, pronounced artifact emergences, which are reflected in crossfade phenomena, occur particularly in the transition from FRP to metal [5]. Therefore in the hole edge region of a self-pierce riveted joint, where delaminations occur increasingly, no exact statements can be made about their extent.

In self-pierce riveted composite-metal joints, clamping forces act below the flat head to be used normally in the plane of the joined parts. These clamping forces can ensure that - under certain circumstances – delaminations formed in the punching process are compressed and closed. In this way, these void spaces are removed and can no longer be detected by computer tomography or other test methods.

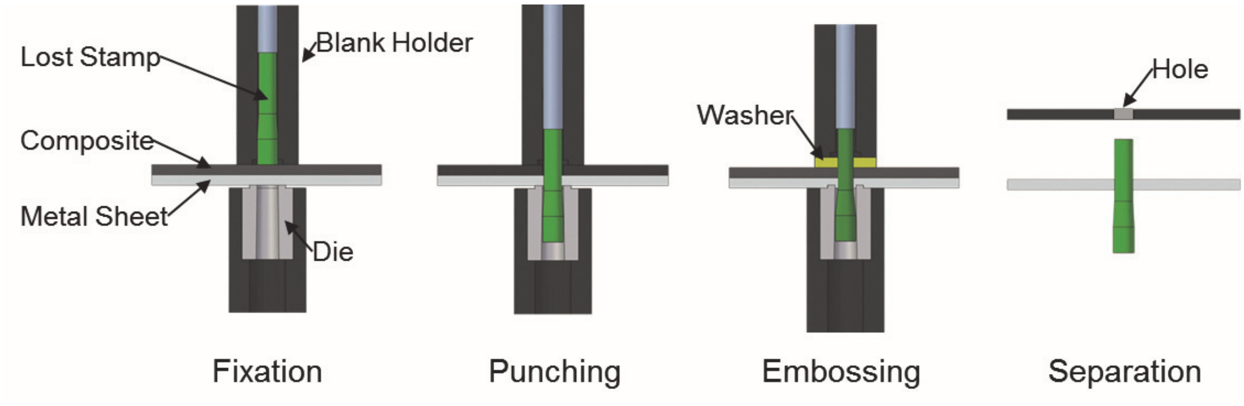

Fig. 3. Preparation of specimens based on the self-pierce riveting process

For these two reasons mentioned, a specimen must be found that allows a separation of the fibre-reinforced plastic from all metal and in which no clamping forces prevail. Using the example of solid self-pierce riveting a method developed at the LWF will be explained as shown in Fig. 3.

The aim is to prepare samples that meet the above-mentioned requirements, but are still produced under the real process conditions of solid self-pierce riveting. For this reason, a methodological concept was developed that uses conventional solid self-pierce riveting facilities and tools. In this concept, fibre composite and metal sheets are punched by a lost stamp, which does not remain in the materials. In this way, no connection has been made and the components can be separated from each other.

The lost stamp can be inserted in a specially designed blank holder. This has a diameter of 4.0 mm at the function area on the basis of the shaft diameter of common fibre reinforced plastic suitable solid self-pierce rivets, and tapers via an extensive bevel up to 3.0 mm. Thus the punch can pierce the hole and be driven in so far that it can be removed from the bottom without manipulating the joining parts.

The blank holder with the inserted lost punch is fitted on the parts to be joined and clamps them with a preload force. The rivet pin moves further, until the punch touches the joining parts and pierces the hole due to increased force. In the blank holder a blind hole is added, which simulates the flat head of the rivets during the punching process. Under the flat-head the joining parts cannot be clamped, so increased incidence of delaminations in this area is to be expected. Thus, the fibre composite is clamped with this blank holder concept in an annular region around the lost punch.

Subsequently the punch is driven in far enough for the tapered shank to locate in the pierced hole. Rivet pin and blank holder are moved back and a washer is placed underneath which has an outer diameter of the same size as the blank holder and an inner diameter of the shank thickness (4.0 mm). The shaping step can therefore now be carried out under real conditions. Without the washer, material would be pressed up into the blind hole due to the lack of underpinning, which would be accompanied by a strong material damage of the composite. Finally, the sample is removed and the fibre-reinforced plastic can be separated from the remaining parts.

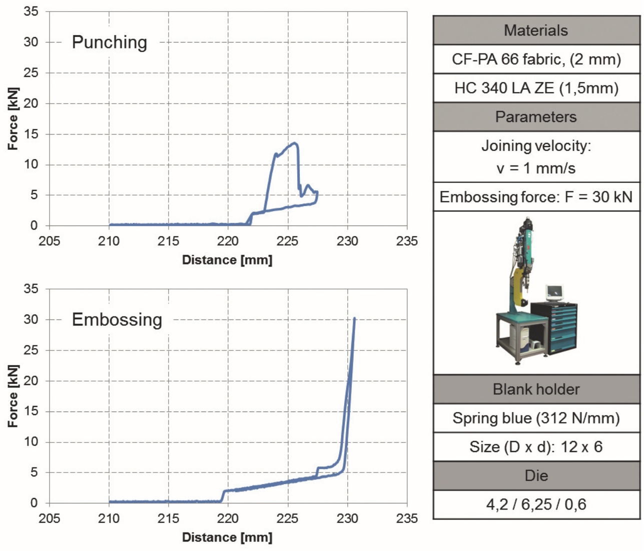

Fig. 4. Force-distance diagrams of the two-part sample preparation process

Figure 4 shows the two-part process. The upper diagram reflects the punching process. It yields a maximum force of 13.57 kN, which includes the spring force of the blank holder, however. After adjustment to take account of this, the punching force amounts to 10.43 kN. In the second step the shaping operation is carried out with a maximum force of 30 kN. Please refer to the illustration for other process parameters.

In order to describe existing correlations between process parameters and damage extents, several parameter variations are tested and scanned by the X-ray computed tomography. The joining speed is investigated, since the polymeric matrix system shows a loading rate dependence [6]. Similarly, the surface pressure is varied with various blank holder forces while punching, which generates a distinct complex stress state. According to the Drucker-Prager criterion, polymers can become brittle as their hydrostatic proportion increases, so that fibre composites can also display a different failure behaviour [7]. Variations in blank holder dimensions determine the size of the clamped and unclamped areas. Besides various cutting gaps, maximum process forces and die contact faces are also examined, allowing the damage influence during embossing to be investigated.

In addition, various combinations of materials are investigated. On the one hand the micro-alloyed steel HC 340 LA and the wrought aluminium alloy AC-600 PX in 1.5 mm thickness are used. The combinations with aluminium are joined in T4 temper. On the other hand carbon-fibre reinforced plastic fabrics with polyamide 66 matrix and non-woven multidirectional carbon fibre fabrics with epoxy resin matrix are investigated. The latter materials are produced by wet pressing process, using resin XB 3585 and hardener XB 3404 from Huntsman. The glass transition temperature was checked by DMA and amounts to 84 °C. The structure of the laminate is built up in accordance with a laminate system optimized for pin load: (0°2/90°/45°/-45°)S. The fibre volume fraction amounts to 56 %.

Several parameter combinations are generated and scanned by computer tomography in order to determine the sensitivity of the correlation between individual variables and degrees of damage. Since the extent and form of delaminations are highly susceptible to statistical fluctuations, five repetitions are provided per series.

3. Results and Discussion

If samples are made of CF-PA 66 and HC 340 LA, it is noticeable that radial cracks on the surface starting from the hole edge were created. These cracks can be identified as fibre breakage, which can easily be shown on the warp and weft yarns of the fabric. It can be assumed that these surface cracks are caused by tangential strains, which suggests that the punch pierces smaller holes than 4.0 mm and is pressed into the hole. This press fit results in a strong elastic stretch of the fibre composite in the hole edge region in tangential direction. Due to the low ultimate elongation of the carbon fibres, radial fibre breaks occur in areas where the fibres are arranged tangentially to the hole. However, areas with radial orientation of the fibres to the hole remain undamaged, as the tough thermoplastic matrix can compensate the stretching so that no inter-fibre fractures occur [8].

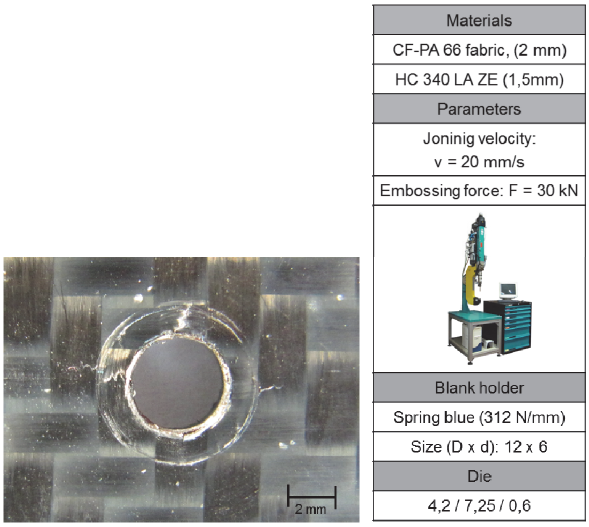

Fig. 5. Punched sample with radial cracks on the surface

This effect can be seen in the right-hand area of Figure 5. Fibres are radially oriented directly at the right edge of the hole, so no crack has occurred there. Breakage can be seen behind this area, as the fibres are arranged tangentially. Special attention must be paid to such cracks, since the composite is severely damaged and further delamination can be induced at these points.

This effect can be explained with the punching behaviour of FRP metal composites. Since the composite material is always arranged as the top layer, the material is shear-cut on the upper side directly at the sharp cutting edge of the punch. However, on the underside a trough is formed in the metallic joining partner, so that a local biaxial bending of the composite occurs. Since there are no defined cutting conditions, the material is not cut, but breaks off.

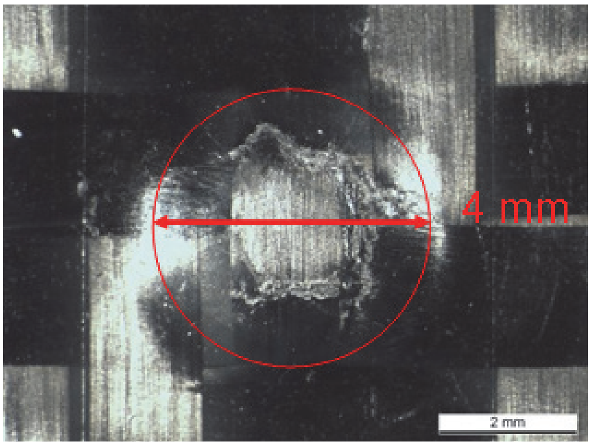

Fig. 6. Bottom of a nearly punched CFRP specimen

Figure 6 shows a sample shortly before punching through. For this the above-mentioned punching process was carried out with a maximum force of 300 N below the punching force. The pronounced bulge on the underside and first fibre breaks on the surface are clearly visible. As can be seen, these cracks originate within the cutting diameter of 4 mm. It can therefore be assumed that the pierced hole exhibits a diameter smaller than 4 mm. Thus, the elastic pressing in of the punch partially bursts the composite material. These cracks extend beyond the flat head and are therefore to be regarded as particularly critical.

Figure 7 shows centric sectional views of CF-PA 66 samples. In each case, five samples of the same series were arranged into stacks and scanned together. It is conspicuous that in the hole edge region the individual fibre layers are deformed downwards with the punching direction. This also implies that the elastic penetration of the punch causes strong transverse forces towards the base sheet that irreversibly deform the composite. Thus, carbon fibre reinforced plastic particles can easily be drawn into the base sheet and hinder the undercut connection during embossing.

The punch holes can be exactly measured in the sectional images. It is found that the holes expand conically toward the base sheet, since the lower layers are less underpinned and more liable to bend away. On average, the sections the holes exhibit a diameter of 3.6 mm at the entry side and 3.8 mm at the exit side of the punch. As mentioned above, the hole must be widened elastically if a rivet shank diameter of 4.0 mm is inserted later.

Occasionally, delaminations can be seen in the area of the hole edge. However, these are very limited in their extent, which is due to the high ultimate elongation and toughness of the polyamide matrix [8].

4. Conclusions

As part of a research project, the laminate damage in self-pierce riveting processes of FRP-metal joints is investigated. Particular attention is paid to the detection of delaminations, which is why samples are tested non-destructively by computer tomography.

Since all metal parts must be avoided in the scans, a method for the preparation of specimens depicting real self-pierce riveting processes was developed. It has been shown that the punched holes exhibit a smaller diameter than the punch. In this way, the punch is elastically pressed into the material, so that fibre breaks extending radially emerge on the surface of the fibre composite. Initial CT scans with exact measurements of the holes confirmed this point and show the existence of delaminations in the hole edge region which, however, are small.

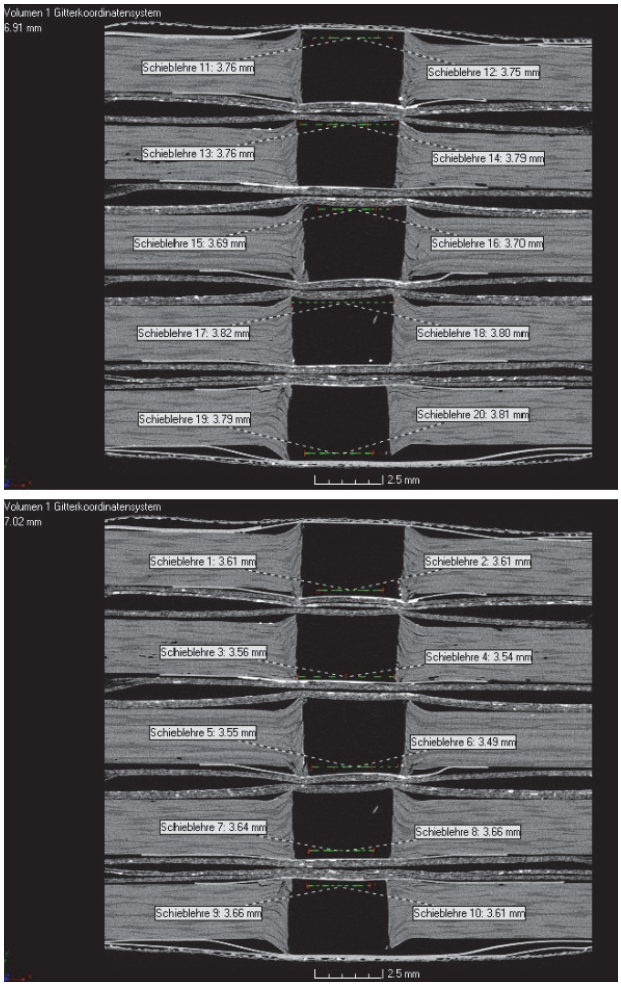

Fig. 7. Centric sectional view of CT scanned punched samples

The next steps planned are to accurately measure the delaminations volumetrically and to develop a three-dimensional model of them. Furthermore, various process parameter configurations will be tested and evaluated. In parallel, a method will be developed to prepare samples depicting the semi-tubular self-pierce riveting process. Finally, the influence of damage on the structural behaviour of composite joints will be determined in quasi-static and cyclic tests.

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